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Summary

RAVEN, a 5 kJ, 1.5 MV repetitive pulser, was built to test the performance of high voltage transformer pulse-charging systems. The pulser has a 4 nF water-insulated, pulse-forming line which is charged by a bipolar primary capacitor bank through a voltage step up pulse transformer. Both the primary capacitor and high-voltage output switches are gas dynamic spark gaps which have been operated at sustained pulse rates up to 20 pps. The system operates with an overall energy transfer efficiency slightly better than 90%. A description of the system and its performance characteristics will be discussed. Specific design features of the switches and transformer will also be included.

Introduction

The RAVEN pulser (Fig. 1) is an upgraded version of an earlier 1.5 MV repetitive pulser system¹ which operated with an energy per pulse of 1.4 kJ. The new system has six rather than two primary capacitors and a larger secondary capacitor to accommodate the increased energy. The same pulse transformer and secondary switch were used in both systems. The transformer is an air core unit which was operated in a dual resonance charge mode. With the primary and secondary sections properly tuned, the systems operated with a 93% overall energy transfer efficiency.

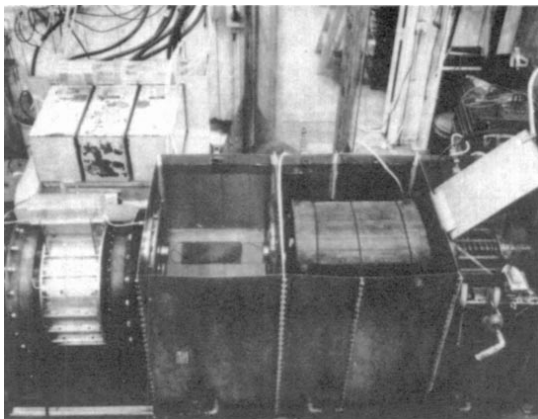


Figure 1. The RAVEN pulser system

Both systems were designed for continuous 10 Hz operation. The earlier system, however, was operated as high as 20 Hz for sustained periods. Neither the water-cooled primary spark gaps or the high voltage secondary spark gap overheated with test runs as long as 100,000 pulses at 20 Hz. Prefiring of the primary switches did not occur with recharge periods as short as 4 ms. Under these conditions the compressed air required was nearly 30 scfm. To reduce the air demand for the larger RAVEN system, additional inductance was added to the resonant charging supply which increased the recharge period

to 21 ms. Interstage switching was not used between the power supply and primary capacitors in either case to give the spark gaps a zero-voltage grace period for recovery.

Primary Capacitor Bank and Switches

The primary capacitor bank was arranged in an over-under configuration (see Fig. 2) with three 1.85 μ F parallel capacitors on each side. The output load plates, connected to the capacitor cases, were lead out between the top and bottom rows and attached to the pulse transformer at the rear of the assembly.

CAPACITOR BANK

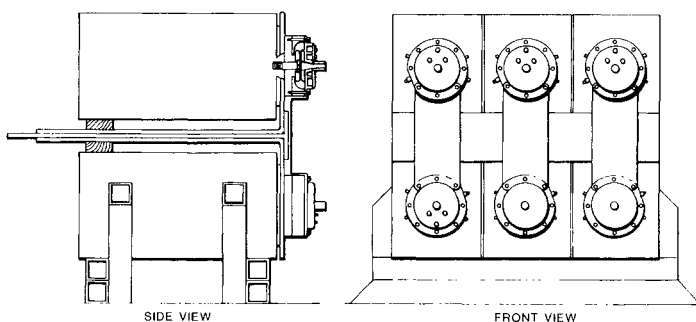


Figure 2. Capacitor bank arrangement

Individual two-electrode spark gap sections² were attached to each capacitor's high voltage terminal with the switch outputs at the positive side connected in parallel to those of the negative side, forming three switch pairs. The switches were triggered by applying a high voltage pulse to the output terminal of each switch section through a coupling capacitor and series spark plug as shown in Fig. 3.

The switch sections are two-electrode spark gaps which have 80 cm² flat button electrodes for long life. Both electrodes were water cooled. They could, therefore, be operated continuously without periodic cool-off periods. Air was injected tangentially into the switch volume through nozzles located in the housing. This arrangement produced a vortex flow pattern through the electrode gap which was exhausted through a port in the center of the output electrode.

Since the switches have relatively high capacitances and no field-enhanced trigger elements, it was necessary to trigger them with a low impedance, high-voltage trigger generator. A special transformer (Fig. 4), designed for this purpose, delivered a 200 kV pulse from a 250 pF secondary capacitor through an output peaking gap to six parallel trigger leads. The transformer had a 30 nF primary capacitor charged to 20 kV. The secondary capacitor in combination with the trigger leads had an impedance of approximately 20 ohms compared to the direct output impedance of the transformer which was about 900 ohms.

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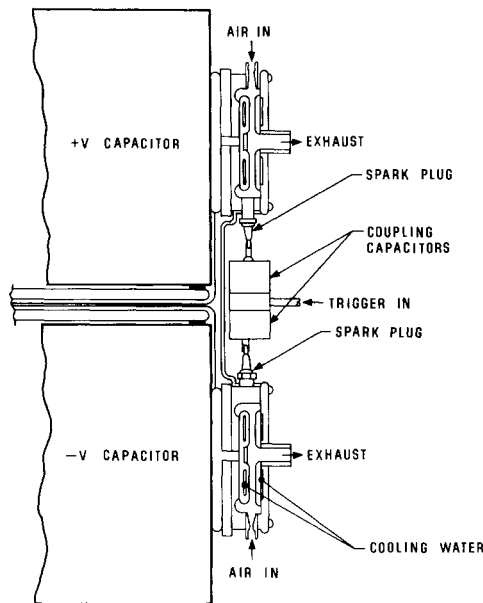


Figure 3. Two-section spark gaps

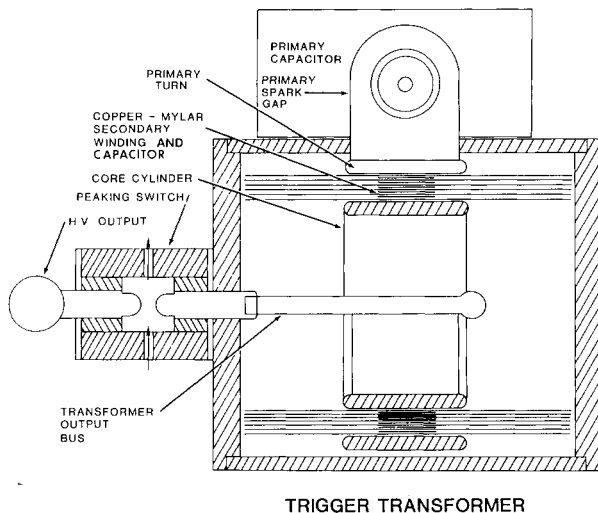


Figure 4. Trigger Transformer

Pulse Transformer

The main voltage step up transformer³ was an air core unit which is shown in cross section in Fig. 5. It has a single turn primary surrounding a 42-turn secondary winding. The active width of both windings is 30 cm. The turns of the secondary winding are insulated with 60 cm wide polyester film.

The margins of the transformer are enclosed in a concentric ring cage which grades the voltage outside the edges of the secondary winding and prevents highly enhanced electric fields from occurring along the edges of the turns which could cause insulation breakdown. Each outside ring has one circumferential gap to prevent current from being induced in it. The inner ring structure is divided into four segments to enhance its response to fast transient voltages. In all cases the rings and segments are electrically connected along one line opposite the gaps.

For structural reasons the transformer case was made of filament wound fiberglass reinforced polyester tube sections with integral flanges. The flanges support the acrylic end plates of the transformer and provide a rigid connection to the external load system. The primary turn, located in the center of the assembly, is also flange-connected to the case and forms an intermediate structural component.

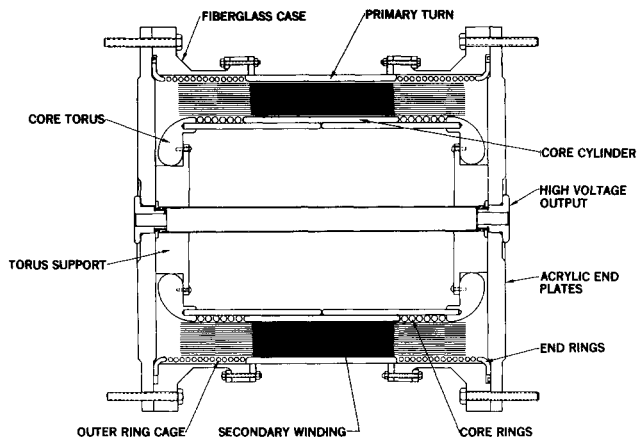


Fig. 5. Pulse Transformer

Load Section

The transformer was coupled to a load section consisting of a tuning inductor, a 4.1 nF, 5 Ω , water insulated pulse forming line (PFL), a self-breaking spark gap and a water resistor. The self-break voltage of spark gap was controlled by adjustment of the gas pressure in the gap.

The PFL was a coaxial arrangement built into a box section 75 cm long and produced a pulse of approximately 50 ns duration. The output switch⁴ was a stacked insulator type spark gap with a recirculating axial gas flow pattern between the electrodes. This switch was developed during the testing of the earlier 1.4 kJ system where, with axial gas flow, it demonstrated greatly improved switching stability compared to a vortex flow pattern (see Fig. 6). The improved performance with the axial flow pattern was attributed to the enhanced gas flow directly against the electrode surfaces and the improved turbulent mixing of gas between the electrodes.



Figure 6. Comparison of high voltage switch stability with vortex and axial gas flow patterns

- (a) switch breakdown with vortex gas flow pattern gas volume, 17.3 scfm
- (b) switch breakdown with axial gas flow pattern gas volume, 10.8 scfm

Operational Results

The transformer system was operated in a dual resonance charge mode which involved tuning the primary and secondary sides of the circuit to the same frequencies and adjusting the circuit coupling coefficient to 0.6. Tuning the circuit in this manner involves adding appropriate inductances to both sides of the transformer circuit.

Knowing the inductances of the transformer and the primary and secondary capacitances, the tuning inductances were found by combining the frequency and coupling equations to find the values of tuning inductance. Using the relation for coupling coefficient, (K), is set equal to 0.6.

$$K = \frac{M}{\sqrt{L_1 L_2}} = 0.6 \quad (1)$$

where M is the mutual inductance of the transformer.

The values of total primary and secondary inductance, L_1 , and L_2 , become

$$L_1 = \frac{1}{L_2} \left(\frac{M}{0.6} \right)^2 \quad (2)$$

$$L_2 = \frac{1}{L_1} \left(\frac{M}{0.6} \right)^2 \quad (3)$$

Since $L_1 C_1 = L_2 C_2$, substitution gives,

$$L_1 = \frac{M}{0.6} \sqrt{\frac{C_2}{C_1}} \quad (4)$$

$$L_2 = \frac{M}{0.6} \sqrt{\frac{C_1}{C_2}} \quad (5)$$

The tuning inductance, L_{t-1} , for the primary and L_{t-2} for the secondary became

$$L_{t-1} = L_1 - (L_p - L_b)$$

$$L_{t-2} = L_2 - L_s$$

where L_p is the primary inductance of the transformer (650 nH); L_b is the inductance of the capacitor bank (110nH); L_s is the inductance of the secondary winding (488 μ H).

Using these relations, tuning inductors of 187 nH and 125 nH were added to the primary and secondary circuits. The resulting charge cycle is shown in Fig. 7 which is a ringdown waveform for the dual resonance condition. Figure 8 is a charging pulse switched near the peak of the reverse voltage excursion.

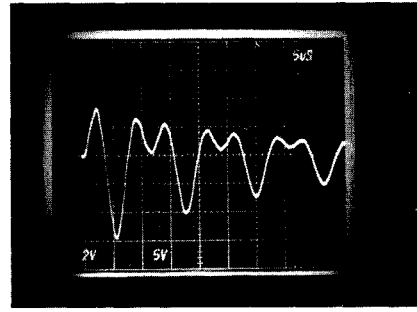


Figure 7. Dual resonance ringdown waveform for the RAVEN system



Figure 8. Secondary voltage waveforms from capacitive (top) and resistive (bottom) monitors

System tests included a variety of short to long runs at pulse repetition rates from 1 to 10 Hz with output voltages ranging from 750 kV to 1.5 MV. From these data the transfer efficiency was obtained and general system performance observed. When the resistivity of the water in the pulse forming line (PFL) was held in the range of 9 to 10 M Ω -cm, the energy transfer efficiency from the primary capacitors to the PFL was measured at 93%. Other features of performance were evaluated in terms of their breakdown endurance and drift in characteristics as a results of sustained pulsing. No problems with switch, capacitor, or transformer overheating were observed in any test run. The only major difficulty encountered was a gradual reduction in dielectric strength and periodic breakdown of the oil in the high voltage switch tank as a result of low level corona forming around the switch.⁵ This effect occurred when the system operated above 1 MV for test runs over approximately 20,000 pulses. The oil would fully recover its strength between test runs if at least a four-hour quiescent period was allowed. During test runs, however, the corona effect was minimized by continuous circulation and filtering of the oil.

Conclusions

Throughout the testing of the RAVEN pulser, the system and its components operated with high efficiency and reliability. The only real problem encountered was with the corona in the insulating oil of the switch tank. This problem could be alleviated by operating with lower electric fields. The exact field strength for complete corona free operation has not been established. The principal objective of the experiment, however, was accomplished and that was to demonstrate transformer charging system performance above 1 MV in a continuous running repetitive pulser.

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